Assessing the probability of crown fire initiation based on fire danger indices

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The initiation of crown fires in conifer stands was modelled through logistic regression analysis by considering as independent variables a basic physical descriptor of the fuel complex structure and selected components of the Canadian Forest Fire Weather Index (FWI) System. The study was based on a fire behaviour research database consisting of 63 experimental fires covering a relatively wide range of burning conditions and fuel type characteristics. Four models were built with decreasing input needs. Significant predictors of crown fire initiation were: canopy base height, wind speed measured at a height of 10 m in the open, and four components of the FWI System (i.e., Fine Fuel Moisture Code, Drought Code, Initial Spread Index and Buildup Index). The models predicted correctly the type of fire (i.e., surface or crown) between 90% and 66% of the time. The C index, a statistical measure, varied from 0.94 to 0.71, revealing good concordance between predicted probabilities and observed events. A comparison between the logistic models and Canadian Forest Fire Behaviour Prediction System models did not show any conclusive differences. The results of a limited evaluation involving two independent experimental fire data sets for distinctly different fuel complexes were encouraging. The logistic models built may have applicability in fire management decision support systems, allowing for the estimation of the probability of crown fire initiation at small and large spatial scales from commonly available fire environment and fire danger rating information. The relationships presented are considered valid for free-burning fires on level terrain in coniferous forests that have reached a pseudo steady-state and are not deemed applicable to dead conifer forests (i.e., insect-killed stands).

Key words: Canadian Forest Fire Danger Rating System, crown fire initiation, fire behaviour, fire danger indices, logistic regression

L'amorce des feux de cime dans les peuplements résineux a été modélisée au moyen de l'analyse d'une régression logistique en considérant comme variables indépendantes un descripteur physique de base de la structure de l'ensemble formant le combustible et certains éléments choisis du Système canadien d'indice météorologique des feux de forêts (IMF). L'étude reposait sur une base de données de recherche sur le comportement du feu constituée de 63 feux expérimentaux rassemblant un assez grand éventail de conditions de brûlage et de caractéristiques du type de combustible. Quatre modèles ont été élaborés en fonction de la décroissance des intrants requis. Les prédicateurs significatifs de l'amorce des feux de cime étaient : la hauteur moyenne des cimes, la vitesse du vent mesurée à une hauteur de 10 m dans un espace ouvert, et quatre composantes du Système IMF (c'est-à-dire, le code d'humidité des particules fines de combustible, le code de sécheresse, l'indice de répartition initiale et l'indice d'accumulation). Les modèles ont prédit avec exactitude le type de feu (c'est-à-dire, de surface ou de cime) entre 90 % et 66 % du temps. L'indice C, une mesure statistique, a varié entre 0,94 et 0,71, démontrant une bonne concordance entre les probabilités prédites et les événements observés. Une comparaison entre les modèles logistiques et les modèles du Système canadien de prédiction du comportement des feux de forêts n'a révélé aucune différence significative. Les résultats de l'évaluation restreinte à deux ensembles de données sur des feux expérimentaux indépendants comportant des complexes de combustibles distinctement différents ont été encourageants. L'élaboration de modèles logistiques pourrait avoir une application dans les systèmes d'aide à la prise de décision pour la gestion des feux, permettant un estimé de la probabilité de l'amorce des feux de cime à petites et à grandes échelles dans le cas des situations courantes de feux et en fonction de l'information sur le niveau de danger associé aux feux. Les relations présentées dans cet article sont considérées être valides pour les feux non contrôlés en terrain plat dans des forêts de conifères qui ont atteint un pseudo état d'équilibre et ne sont pas utilisables pour les forêts de conifères mortes (par ex. les peuplements ravagés par des insectes).

Mots-clés: Système canadien de classification des feux de forêt, amorce des feux de cime, indices de danger relié aux feux, régression logistique

Introduction

The knowledge of fire behaviour is a fundamental component of any fire management system, allowing for the determination of the impact of fire on several ecosystem components, assessment of the effectiveness of fuel treatments, and support for decision-making in wildfire suppression planning and in forest management activities that

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require the use of fire as a tool (Barrows 1968, Countryman 1972). Models for predicting wildland fire behaviour are commonly used operationally by land management agencies in North America (Pyne *et al.* 1996). Wildland fire research has produced models that enable important fire characteristics to be predicted within acceptable precision for most current field applications. Nevertheless, our fire behaviour "dictionary of ignorance" is still broad (Saveland and Thomas 1998), and a complete fundamental description of a fire front and its impacts on ecosystem components is still largely lacking.

Crown fire initiation has been one aspect of fire behaviour where the current state of knowledge has been limited. From a fire management perspective, knowledge of the onset of crowning is of critical importance from a safety and tactical standpoint, yet few research attempts have been directed at explaining and/or developing models to predict this feature of wildland fire behaviour (Van Wagner 1977a, Xanthopoulos 1990, Alexander 1998, Cruz 1999). This lack of attention probably can be explained by (1) the unknowns in fundamental combustion and heat transfer theory in wildland fuels, (2) the difficulty in replicating such phenomena in a laboratory setting, and (3) the difficulty of instrumenting outdoor high-intensity experimental fires in order to quantitatively describe the influence of relevant variables, important physical processes, and their outcomes.

In Canada, operational fire behaviour prediction currently relies primarily on the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992, Taylor *et al.* 1997) a subsystem of the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks *et al.* 1989). This empirically based system relies in part on statistical relationships between fire weather and fire danger indices of the Canadian Forest Fire Weather Index (FWI) System[4], the other major subsystem of the CFFDRS, and fire behaviour data garnered from experimental fires and wildfires in specific fuel types (Alexander and Quintilio 1990, McAlpine *et al.* 1990, Van Wagner 1998).

In the FBP System, crown fire initiation is estimated through the use of the Van Wagner (1977a) crown fire initiation model, which takes into account foliar moisture content and the height to live crown base as a means of defining the energy requirements for canopy ignition and the corresponding surface fire intensity (Byram 1959) as a measure of the heat source. Van Wagner's (1977a) heat balance physical/empirical formulation to define the onset of crowning encompasses relationships from existing theory and experimental outdoor crown fires. Although this model has been embraced by many members of the wildland fire research community in North America (e.g., Bessie and Johnson 1995, Agee 1996, Scott 1998, Graham *et al.* 1999), and currently integrates various types of decision aids and decision-support systems for fire management (e.g., Alexander 1988, Forestry Canada Fire Danger Group 1992, Finney 1998, Scott and Reinhardt 2001), it has never been subjected to a formal model evaluation. It possesses several theoretical and practical limitations, namely: (1) its heat of ignition formulation assumes that all the moisture must be driven off before ignition (Xanthopoulos 1990, Alexander 1998), whereas the occurrence of simultaneous drying and pyrolysis (Saastamoinen and Richard 1996) is expected under high energy fluxes such as the ones verified at the onset of crowning; (2) the proportionality constant has been assumed to be universal, although recent research (Alexander 1998) indicates that it is not the case—it is expected that it is dependent on combustion characteristics as determined by surface fuel bed structural properties and fuel moisture dynamics (Cruz 1999); (3) the model is based solely on convective theory, whereas the radiative component might predominate in some burning conditions; (4) the use of Byram's (1959) fire intensity variable requires the estimation of rate of fire spread and fuel consumption from other models, inducing an error propagation problem and increasing the uncertainty of the model system.

The objective of this study was to develop a model to predict the probability of crown fire initiation following the modeling approach similar to that used in the development of the FBP System and other additions of the CFFDRS (Lawson and Dalrymple 1996, Lawson *et al.* 1997).

It is worth acknowledging that this is not the first attempt to devise a scheme for judging crown fire potential using components of the FWI System (e.g., Lawson 1973, BCMF 1983), other than using specified ISI or FWI values as crown fire thresholds (Alexander and De Groot 1988, Alexander and Lanoville 1989, Lawson *et al.* 1985). Van Wagner (1974b) developed a special index called the Crown Spread Index (CSI) that was obtained simply by multiplying the ISI value by a Crown Spread Factor (CSF), which was in turn based on a particular season trend in foliar moisture content. The CSF varied from 1.0 to 2.2 and was linked to calendar data for operational ease of use. Crown fires in pine stands, for example, were expected to occur when the CSI exceeded 30. Fuglem and Murphy (1980) constructed graphs linking the standard FWI component-fire intensity relationship found in the FWI System (Van Wagner 1974a, 1987) to Van Wagner's (1977a) criteria for crown fire initiation as dictated by foliar moisture content and live crown base height. Level terrain was assumed in both of these schemes. For whatever reason, neither of these decision aids was ever widely applied.

Methods

The approach used in this study relies in large part on an extensive, experimental fire behaviour database for natural conifer forest stands. The compiled database consists of 63 observations involving both surface fires and crown fires set for the purpose of studying fire behaviour in relation to the prevailing fuel and weather conditions. The fact that the data have been obtained from outdoor experimental fires implies that there is a high degree of reliability in the documentation of the fire behaviour characteristics and attendant burning conditions. No data from wildfire case studies (Alexander and Lanoville 1987) were used, mainly because they do not provide sufficiently precise information on the fuel complex characteristics and fire

[4]The FWI System consists of six relative fire danger indices each of which is designed to represent some aspect of fire behaviour (Van Wagner 1987). The Fine Fuel Moisture Code (FFMC) is a numerical rating of the moisture content of litter and other cured fine fuels. The Duff Moisture Code (DMC) is a numerical rating of the average moisture content of loosely compacted organic layers of moderate depth. The Drought Code (DC) is a numerical rating of average moisture content of deep, compacted, organic layers. The Initial Spread Index (ISI) is a numerical rating of the effect of wind and FFMC on rate of spread without the influence of variable quantities of fuel. The Buildup Index (BUI) is a numerical rating of the total amount of fuel available for combustion that combines DMC and DC. The Fire Weather Index (FWI) itself is a numerical rating of fire intensity that combines ISI and BUI.

environment conditions at the time of transition from surface to crown fire spread. The compiled database used in the present study constitutes a subset of that used in the development of the FBP System (Forestry Canada Fire Danger Group 1992). The experimental fire data is thus based on studies carried out in Canada encompassing several different forest stand types and a wide range of fuel complex structures (Van Wagner 1968, 1977a; Lawson 1972; Kiil 1975; Quintilio *et al.* 1977; Newstead and Alexander 1983; Stocks 1987a, 1989; Weber *et al.* 1987). A detailed description of the database is given elsewhere (Cruz 1999). Table 1 summarizes basic descriptive statistics of the independent variables selected for analysis. Foliar moisture content, canopy base height, and wind speed are three fire environment variables that theoretically are major factors controlling the onset of crowning and have already been used in modeling this phenomenon (Van Wagner 1977a, Xanthopoulos 1990, Alexander 1998; Cruz *et al.* 2002). The range and deviation around the mean for these variables suggest a balanced distribution suitable for the statistical analysis to be pursued in the present study. The FWI System fuel moisture codes and fire behaviour indices associated with the experimental fires cover a relatively wide range of conditions under which crown fire initiation is known to occur.

Given the dichotomous nature of the event under study (i.e., occurrence or not of crowning), a logistic regression approach allowing the estimation of the probability of an event occurring from a combination of fire environmental factors is appropriate. Multiple logistic regression models were fitted relying on SPSS 8.0 statistical package (Norusis 1997). The multiple logistic regression model has the following form (from Hosmer and Lemeshow 2000):

$$P(y_i = 1) = \frac{e^{g(x)}}{1 + e^{g(x)}} \quad (1)$$

being the logit given by the equation:

$$g(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i \quad (2)$$

where, $P(y_i = 1)$ is the probability of crown fire occurrence, x_i are the independent variables, and β_i are the coefficients estimated through the maximum likelihood method, which will produce coefficients that maximize the probability density as a function of the original set of data. A decision criterion of 0.5 as the threshold of crown fire initiation was assumed. This cutoff value has been commonly used to discriminate the continuous model response in the interval between 0.0 and 1.0 (e.g., Wilson and Ferguson 1986, Ryan and Reinhardt 1988, Wilson 1988, Borchert *et al.* 2002).

Model fit was assessed through the Nagelkerke (1991) R^2 value and the C index (Hanley and McNeil 1982, Regelbrugge and Conard 1993). The Nagelkerke R^2 attempts to quantify the proportion of explained variation in the logistic regression model. It is a redefinition of the conventional coefficient of determination (Cox and Snell 1989) so that a maximum value of 1.0 is attained when all observations are correctly predicted. The C index, which ranges from 0.5 (no discrimination) to 1.0, analyzes model fit through the relation between the predicted probabilities and the observed events. It is equivalent to the area under the "receiver operating characteristic" curve (Hanley and McNeil 1982, Saveland and Neuenschwander 1990) for a binary dependent variable, and is independent of the decision criteria (Regelbrugge and Conard 1993). Two independent data set comprising a total of 19 experimental fires in two very diverse fuel complexes were used to evaluate general model performance (Alexander *et al.* 1991, 2001).

Table 1. Basic descriptive statistics of independent variables contained in the data set used in the logistic model development (n = 63)

Independent variables	Minimum	Maximum	Mean	St. Dev.
Foliar moisture content (%)	80	135	108.1	8.3
Canopy base height (m)	0.4	12	3.9	3.0
10-m open wind speed (km/h)	3	29	12.6	5.5
Fine Fuel Moisture Code (FFMC)	84.5	94.1	90.5	2.0
Duff Moisture Code (DMC)	9	89	41.4	17.5
Drought (DC)	60	423	193.4	86.9
Initial Spread Index (ISI)	3.2	21.5	9.2	4.0
Buildup Index (BUI)	13	109	51.2	19.4
Fire Weather Index (FWI)	6	43	20.7	8.3
Rate of fire spread (m/min)	0.4	49.4	8.7	10.3
Fire Intensity (kW/m)	62	45200	6322	9342

Results

Given the possible applicability of a crown fire initiation model based on readily available or estimated fire environment variables and FWI System components to support fire management decision-making, four models, LOGIT1 through LOGIT4, were developed, each with decreasing input needs (Table 2). The combination of variables defining the larger model was based on the theoretical weight of the variables on the phenomena under study and an attempt to avoid multicollinearity problems. The probability level used for testing the significance of the various parameters as determined by the maximum likelihood method was set at 95%. The maximum likelihood theory applies strictly to large samples (Smith 1969) which limits the analysis of the statistical results reported in Table 2. All of the variables but the DC in LOGIT4 were significant predictors of crown fire initiation.

All the models in Table 2 have a significant reduction in the –2 Log Likelihood (–2LL) against the initial log likelihood function. Overall, model fit decreases from LOGIT1 to LOGIT4 as seen by the increase in the –2LL and the reduction in the Nagelkerke R^2 statistic. This particular R^2 measure should be interpreted with care, as it is not comparable to the R^2 statistic computed in least squares regression. The R^2 measure proposed for logistic regression models relies on comparisons between the fitted model and a no data or intercept only model, rather than comparing model predictions with observed values (Hosmer and Lemeshow 2000). These measures are better used for model comparison purposes. Overall, LOGIT1 model correctly predicted 90% of the fires in the data set. The remaining models did a poorer job of correctly predicting the type of fire in the database. LOGIT4 had the least discriminating power, correctly predicting 74% of the surface fires and 58% of the crown fires (Table 2). The computed C index (Table 2) varied from 0.94 in LOGIT1 to 0.71 in LOGIT4.

Discussion

The models contained in Table 2 predict the probability of the onset of crowning from logistic regression analysis of the experimental fire data used in the development of several of

Table 2. Parameter values and model fit statistics for the four models developed

Item		Models			
		LOGIT1	LOGIT2	LOGIT3	LOGIT4
Parameter values[a]	Constant	−66.620 (25.93)*	−5.005 (1.62)**	−5.123 (1.70)**	−2.357 (0.98)*
	CBH	−0.993 (0.31)**	−0.862 (0.24)**	−1.039 (0.62)**	
	U_{10}	0.568 (0.18)**			
	FFMC	0.671 (0.29)*			
	DC	0.018 (0.007)**	0.014 (0.005)**		0.002 (0.003)
	ISI		0.672 (0.19)**	0.615 (0.18)**	0.232 (0.08)**
	BUI			0.079 (0.03)**	
Model fit	−2LL	39.16	46.22	46.21	87.53
	Nag. R^2	0.71	0.64	0.64	0.19
	C index	0.94	0.92	0.92	0.71
Correctly predicted (%)	Surface (specificity)	90	80	83.3	74.3
	Crown (sensitivity)	91	88	85	58.3

Note: CBH – canopy base height (m); U_{10} – 10-m open wind speed (km/h); FFMC – Fine Fuel Moisture Code; DC – Drought Code; ISI – Initial Spread Index; BUI – Buildup Index; −2LL = −2 × log likelihood; Nag. R^2 – Nagelkerke R^2; * – significant at $\alpha = 0.05$; ** – significant at $\alpha = 0.01$ (based on Wald χ^2 test).
[a]Standard deviation noted in parenthesis.

the standing timber fuel type models found in the FBP System. Analysis of the behaviour of these newly developed models should take into account the fact that the models reflect the characteristics of the data set.

All the independent variables included in the models have a direct effect in determining crown fire initiation or are surrogates of fire environment factors that directly influence the potential for crowning. Canopy base height, for example, defines the vertical stratification of the fuel complex and influences the amount of energy that is dissipated within the convection column above a spreading surface fire until such time as the canopy fuels become susceptible to combustion and vertical fire growth. Wind directly affects fire behaviour through the increase in the rate of fire spread and in turn the heat energy released, and consequently the upward heat flux.

The FFMC, DC and BUI components of the FWI System are surrogates for the amount of fuels of different types and sizes available for consumption in the flaming stage of combustion. Neither the DMC nor foliar moisture content was found to be significant in any model formulation. This non-significant effect of the DMC was unexpected because on theoretical grounds the fuel layer it is designed to represent (Van Wagner 1987) is presumed to have a stronger impact than the deep duff layer that the DC characterizes. The BUI, which in the FBP System is indicative of the total amount of fuel available for combustion, was in general, inferior to the DC in explaining this aspect of fire potential.

The non-significance of foliar moisture content might be explained by the fact that some of the foliar moisture content values in the data set are not the result of direct sampling but rather estimates from the FBP System sub-model (Forestry Canada Fire Danger Group 1992) for predicting foliar moisture content from geographical location (latitude/longitude), calendar date and elevation (e.g., Call and Albini 1997) or by other means (e.g., Van Wagner 1993), yielding average values and perhaps masking the effect of this variable. It should be noted that both theory (Van Wagner 1977a, de Mestre *et al.* 1989) and laboratory studies (e.g., Van Wagner 1967a, 1967b; Xanthopoulos and Wakimoto 1993) indicate a strong effect of foliar moisture content on crown fire initiation (Van Wagner 1998). Nevertheless the effect of live fuels moisture content on fire behaviour is not well understood (Weise *et al.* 1998) and laboratory studies have not been able to replicate the true thermal environment that characterize high-intensity surface fires, namely the heat fluxes and fluid velocities.

The decision criterion for crowning activity was initially chosen as 0.5, the midpoint of the probability range. Subsequent analysis of the models sensitivity and specificity variation (Hosmer and Lemeshow 2000) showed that this cutoff point maximizes both parameters (Table 2), and consequently it was considered the optimal threshold value by which to discriminate model predictions within the present data set (i.e., the type of fire—surface or crown).

Canopy base height and the 10-m open wind speed were the independent variables that most strongly influenced the initiation of crowning. Model LOGIT4 being dependent on just the ISI and DC is more prone to erroneous results as these two variables cannot encompass all the possible factors and interactions determining the onset of crowning. The marginal results obtained by LOGIT4 demonstrate the importance of including information on fuel complex characteristics when attempting to predict the onset of crowning. The exclusion of canopy base height as an input variable in the model reduced the Nagelkerke R^2 statistic to 0.19, and the percentage of overall correctly predicted cases to 66 % (Table 2).

Model evaluation should be a component of the development process leading to a better understanding of model behaviour and an increase in its credibility. The logistic models (Table 2) were evaluated by comparing their output with other predictive models and against two independent experimental fire data sets. The two independent data sets used for model evaluation were the Porter Lake experimental burning project (Alexander *et al.* 1991) and the International Crown Fire Modeling Experiment (Alexander *et al.* 2001). The Porter Lake data set comprises eight experimental fires in a black spruce–lichen woodland fuel complex (Alexander and Lanoville 1989) and the International Crown Fire Modeling Experiment (ICFME) data set includes 11 experimental fire observations in a mature jack pine stand possessing a substantial black spruce understory.

Comparison of model behaviour with other models describing the same event provides an understanding of possible

Table 3. Crown fire initiation predictions for Canadian Forest Fire Behaviour Prediction (FBP) System fuel type C-6- with variable canopy base heights and the logistic models developed in the present study at three different 10-m open wind speed levels (i.e., 5 / 10 / 15 km/h)[a]

Model	Canopy base height (m)			
	3	5	7	9
	Crown Fraction Burned (CFB)			
FBP System C-6	0.22 / 0.51 / 0.75	0.00 / 0.21 / 0.60	0.00 / 0.00 / 0.28	0.00 / 0.00 / 0.00
	Probability of crown fire initiation			
LOGIT1	0.20 / 0.81 / 0.99	0.03 / 0.37 / 0.91	0.00 / 0.07 / 0.58	0.00 / 0.01 / 0.16
LOGIT2	0.55 / 0.84 / 0.97	0.18 / 0.49 / 0.86	0.04 / 0.15 / 0.53	0.01 / 0.03 / 0.17
LOGIT3	0.87 / 0.96 / 0.99	0.47 / 0.77 / 0.95	0.10 / 0.30 / 0.70	0.01 / 0.05 / 0.23
LOGIT4	0.43 / 0.55 / 0.70	0.43 / 0.55 / 0.70	0.43 / 0.55 / 0.70	0.43 / 0.55 / 0.70

Note: CFB: < 0.1 – surface fire; 0.1–0.89 – intermittent crown fire; > 0.9 continuous crown fire. The surface fire/crown fire transition cutoff value for the logistic models is assumed to be 0.5.

[a] The other defined fuel, fire weather and fire danger conditions were: foliar moisture content – 100%, air temperature – 24.4°C, relative humidity – 26%, days since rain – 9, FFMC – 92.2, DMC – 64, DC – 190, and BUI – 70 (Alexander 1998).

Table 4. Crown fire initiation predictions for the Canadian Forest Fire Behaviour Prediction (FBP) System conifer fuel types with fixed canopy base heights (CBH) and the logistic models developed in the present study at three different 10-m open wind speed levels (i.e., 5 / 10 / 15 km/h)[a]

Model	C-1 (CBH = 2 m)	C-2 (CBH = 3 m)	C-3 (CBH = 8 m)	C-4 (CBH = 4 m)	C-5 (CBH = 18 m)	C-7 (CBH = 10 m)
			Crown Fraction Burned (CFB)			
FBP System	0.08 / 0.38 / 0.72	0.86 / 0.94 / 0.98	0.00 / 0.00 / 0.49	0.83 / 0.93 / 0.98	0.00 / 0.00 / 0.00	0.00 / 0.00 / 0.00
			Probability of crown fire initiation			
LOGIT1	0.40 / 0.92 / 0.99	0.20 / 0.81 / 0.99	0.00 / 0.03 / 0.33	0.08 / 0.61 / 0.96	0.00 / 0.00 / 0.00	0.00 / 0.00 / 0.06
LOGIT2	0.73 / 0.92 / 0.99	0.54 / 0.84 / 0.97	0.02 / 0.06 / 0.31	0.33 / 0.68 / 0.93	0.00 / 0.00 / 0.00	0.00 / 0.01 / 0.07
LOGIT3	0.95 / 0.99 / 1.00	0.87 / 0.96 / 0.99	0.04 / 0.12 / 0.44	0.70 / 0.90 /0.98	0.00 / 0.00 / 0.00	0.00 / 0.02 / 0.09
LOGIT4	0.42 / 0.55 / 0.70	0.42 / 0.55 / 0.70	0.42 / 0.55 / 0.70	0.42 / 0.55 / 0.70	0.42 / 0.55 / 0.70	0.42 / 0.55 / 0.70

Note: CFB: < 0.1 – surface fire; 0.1–0.89 – intermittent crown fire; > 0.9 continuous crown fire. The surface fire/crown fire transition cutoff value for the logistic models is assumed to be 0.5.

[a] The other defined fuel, fire weather and fire danger conditions were: foliar moisture content – 100%, air temperature – 24.4°C, relative humidity –26%, days since rain – 9, FFMC – 92.2, DMC – 64, DC – 190, and BUI – 70 (Alexander 1998).

model deficiencies and their limits of applicability. A limited comparison of the models developed in the present study with the fuel type specific models found in the FBP System models was therefore undertaken (Table 3 and 4) for several of the standing timber fuel types, namely C-1 (spruce-lichen woodland), C-2 (boreal spruce), C-3 (mature jack or lodgepole pine), C-4 (immature jack or lodgepole pine), C-5 (red and white pine), C-6 (conifer plantation), and C-7 (ponderosa pine/Douglas-fir). Detailed descriptions of these fuel types and their specific sub-models can be found in the technical report on the FBP System (Forestry Canada Fire Danger Group 1992) and photographic examples can be found in De Groot (1993) and Taylor *et al.* (1997). Given that the various model inputs differ, model comparison should be based on well-documented burning conditions where all relevant input variables were measured. For present purposes then, the model comparison was done according to the burning conditions that prevailed during experimental crown fire R1 in a red pine plantation at the Petawawa Forest Experiment Station in eastern Ontario as described by Van Wagner (1964), with variable 10-m open wind speeds (i.e., 5, 10 and 15 km/h). In the FBP System a nominal canopy base height is assigned to each fuel type judged susceptible to crowning. There is one exception. Surface and crown fire behaviour in FBP System fuel type C-6 is modeled in a slightly distinct way, by incorporating two equations, one for surface spread and another for crown spread (Forestry Canada Fire Danger Group 1992). This allows for variable canopy base heights. Thus, the FBP System C-6 model was compared against the logistic models on the basis of several CBH levels (i.e., 3, 5, 7 and 9 m, with 7 m being the standard default value).

The evaluation results for the FBP System fuel types were expressed in the form of the crown fraction burned (CFB)[5]. A CFB of less than 0.1 is indicative of a surface fire whereas intermittent crown fires have a CFB between 0.1 and 0.89 and continuous crown fires have a CFB greater than 0.9 (Forestry Canada Fire Danger Group 1992).

There are not necessarily any conclusive trends or differences between the two modeling approaches (Table 3). The FBP System models show a large variability relative to the likelihood of crowning between the various fuel types, being that the system is more likely to predict the initiation of crowning in fuel types C-2 and C-4 fuel types than in the other fuel types, fuel types C-5 and C-7 with relatively high CBHs and in turn low susceptibility to crowning. Due to their different forms, it is difficult to compare directly the outputs from the logistic models with the FBP System models. Examination of Table 4 indicates that for fuel type C-1 and C-3, the FBP System predictions are more conservative than those obtained from the logistic models. The opposite situation occurs for fuel types C-2 and C-4, with the logistic models producing the most conservative predictions.

The logistic models show distinct results. LOGIT1 and LOGIT2 show very similar behaviour and within the logistic models, they produce the most conservative estimates. The integration of wind speed and FFMC into the ISI parameter (for LOGIT1

[5]CFB is a measure of the degree of potential crown fuel consumption expressed as a proportion of the total number of tree crowns and as such constitutes an indication of the probable type of fire activity to be experienced over a burned area for fuel types that are susceptible to crowning.

to LOGIT2) did not cause major changes in model results. LOGIT3 is the least conservative of the logistic models, predicting the initiation of crown fire under fire environment conditions that intuitively would not suggest its occurrence. LOGIT4 results are in-between the other three logistic models, yielding reasonable behaviour, although there is the uncertainty about not accounting for the vertical stratification of the fuel complex. Several studies have developed equations to predict canopy base height from commonly available stand characteristics (e.g., Cole and Jensen 1982, McAlpine and Hobbs 1994, Cruz *et al.* 2003a). In the logistic models presented here, the canopy base height is input-variable. This is in contrast to the FBP System where, except for fuel type C-6, it is, strictly speaking, a fixed value for a given fuel type. Users may still want to select a default value after some trial and error based on local experience, including examination of past incidents.

One limitation of the logistic models is that they do not take into account the effect of any other fuel complex characteristic other than canopy base height in the process of defining the likelihood of crown fire initiation. Canopy bulk density is also an important variable in determining crown fire development (Van Wagner 1977). Agee (1996), for example, has suggested that a minimum canopy bulk density of 0.1 kg/m^3 is needed in order to ensure active crown fire spread in a horizontal dimension. In the models presented here, it is assumed that the canopy bulk density is sufficient to support the onset of crowning in the vertical dimension, although it is acknowledged that the critical threshold value is not presently known.

The results of logistic models applied to the two independent experimental fire data sets are presented in Table 5. The Porter Lake experimental fires had an average CBH of 0.8 m whereas the ICFME fires exhibited an average CBH of ~6.6 m based on the height of the base of the live jack pine and black spruce overstory. The logistic models correctly predicted or classified all the crown fires in the Porter Lake data set. For the ICFME data set, the logistic models correctly classified most of the 11 experimental fire observations as crown fires. Two of the ICFME crown fires were classified as surface fires by all four LOGIT models. One of these two fires did initially advance following ignition as a "wall of flame" via torching and sporadic crowning; this initial burst of high-intensity fire behaviour could have been due in part to edge effects. However, the ambient winds decreased after about five minutes at which time the fire had advanced roughly half way across the experimental plot (i.e., ~75 m). When the winds did finally pick up, the fire had turned into a low-intensity surface fire, at which time crowning activity did not become re-established. In other words, it is likely that this experimental fire was just at the point of surface-crown fire transition for the prevailing fuel and weather condition. It is interesting that the logistic models were able to discriminate this particular experimental fire, as all the other fires behaved as truly active or fully developed crown fires. The other experimental fire that was predicted to spread as a surface fire featured a short, dense black spruce understory that acted as an effective ladder or bridge fuel and is not accounted for in the CBH, which is based on the jack pine and the taller black spruce overstory stems.

Table 5. Results of evaluation of the logistic models developed in the present study against two independent experimental fire data sets – the Porter Lake experimental burning project (Alexander *et al.* 1991) and the International Crown Fire Modeling Experiment (ICFME) (Alexander *et al.* 2001)

Model	Type of fire	Porter Lake (Pred./Obs.)	ICFME (Pred./Obs.)
LOGIT1	Surface fires	0 / 0	1 / 0
	Crown fires	8 / 8	10 / 11
LOGIT2	Surface fires	0 / 0	2 / 0
	Crown fires	8 / 8	9 / 11
LOGIT3	Surface fires	0 / 0	3 / 0
	Crown fires	8 / 8	8 / 11
LOGIT4	Surface fires	0 / 0	2 / 0
	Crown fires	8 / 8	9 / 11

Note: The surface fire/crown fire transition cutoff value for the logistic models is assumed to be 0.5.

Conclusions

The models developed in the present study offer a possible alternative means of estimating the onset of crowning within the context of the CFFDRS, although it is not known if the approach presented in this study is in any way superior to the FBP System. Certainly, one distinct advantage is that the probabilistic outcomes of the logistic models allow users to interpret the results differently from the dichotomous answer regarding the possibility of crown fire initiation provided by the FBP System. Based on user experience with the models in a particular fuel type, threshold scores could be locally defined for the probability of crowning.

Errors associated with the uncertainty in estimating fire environment input variables coupled with the inherent errors in outputs from the fire spread and fuel consumption models used in estimating fire intensity can lead to combined errors of up to an order of magnitude. Thus, exclusion of fire behaviour model outputs, such as rate of spread, fuel consumption or fire intensity as independent variables in the logistic models developed in the present study can be seen as a distinct advantage since the approach eliminates the possibility of error propagation in the process of predicting crown fire initiation. Admittedly, the use of FWI System components can introduce some error into the model system since they are in turn dependent on weather inputs (Turner and Lawson 1978), although at a much smaller scale.

No formal model evaluation procedure, including such components as sensitivity analysis, model soundness, statistical and operational validation was carried out (cf. Cruz *et al.* 2003b), as this was considered outside the scope of this study. Such evaluation would be required to better understand model behaviour and assess the applicability of the models to fuel complexes distinct from the ones used in model development.

By the very nature of the data used to develop the logistic models described here, the predictions are deemed relevant solely to live, conifer-dominated forests that are susceptible to crowning as opposed to disease or insect-killed stands (Stocks 1987b). Fires are assumed to have reached a "quasi" steady-state spread rate and intensity for the prevailing burning conditions (Catchpole 2002). Furthermore, model predictions are valid only for level terrain and no allowance is made for the effect of slope steepness (Van Wagner 1977b) in determining crown fire initiation.

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